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Smart Grid Facing the New Challenge: the Management of Electric Vehicle Charging Loads

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Abstract

Because of the energy shortage, air pollution and greenhouse gas over mission, the plug-in electric vehicles can be looked as the alternative of the current fossil fuels vehicles. But PHEVs charging brings out the serious problem to the power systems security operation. Smart grid, with its flexible operation ways, is likely to solve this problem. This paper discusses the relationship between the smart grid and the PHEVs charging load. Then introduce the PHEVs influence on the power system based its different operation model. The third part presents the coordinated charging schedule model and in the last part, some core technologies to construct the communication net are also discussed.

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1. Introduction

The energy shortage, air pollution and greenhouse gas over emission, are the three serious issues the world is facing today [1]. As the alternative of the current popular fossil fuels vehicle, plug-in hybrid electric vehicle (PHEV) and the pure battery electric vehicles (EV) (for simplification, these two types intending vehicles are uniformly called PHEV in the following part of this paper) are looked as an effective way to solve these problems. But, because of the huge amount of power consuming demand to charge the batteries upon these PHEVs or EVs, the power grid operation safety and its current management methods face the great challenge.

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So far, some studies are mainly focus on the influence of the battery charging on the grid and then the optimizing charging schedule [2~8]. And the other papers put their research emphasis on the realization of the concerned technologies, such as the communication ways or the charging control strategy [9, 10]. Therefore on the basis of these researches, this paper tries to develop the novel architecture to describe the interactions between the PHEVs and the power grid. And from this descriptive model, we can easily understand that only the smart grid have the ability to manage the PHEVs charging process.

2. Smart Grid and the PHEVs Charging Problem

Before discuss the challenge of the PHEVs charging to the power grid, it's necessary to analysis the interactions between these two different systems. We know that the PHEVs always run on the road and park at the stopping place and these vehicles are charged by either plugging into electric outlets or by means of on-board electricity generations. Therefore, as to PHEVs charging problem, the power energy consuming location, where the power energy flows from the grid into the batteries, has strong affinity with the geographical space. In the other words, the vehicles flux in one area, the parking places, and the transportation management method will influence the PHEVs charging power energy consuming places. All these factors compose of the so-called transportation net. On the other hand, the electric energy is transferred only via the distribution grid, which limits the energy flowing in the transmission lines. Although compared with the road reconstruction, it's easier to set up the city transmission lines no whether the cost or the construction convenience. But it's still difficult to reconstruct the distribution grid in a large scale to meet the PHEVs charging requirements. So, on the view of the electric power energy flowing, the PHEVs charging process can be looked as the electric energy flowing from the power grid to the batteries of PHEVs under the limitation of the time and geography space.

The other problem is that no whether the road vehicles flux or the power energy flowing in the power lines are changed all the time. This increases the difficulty of PHEVs charging management. Obviously, it is impossible for us to reinforcing the wiring to build the enough robust power systems to satisfy the PHEVs charging load. So, smart grid, with the flexible control characters, has the potential to successful manage PHEVs charging load. Thus, communication net, no matter what type it is, is indispensable to be the information exchange bridge between the transport net and the power grid. Therefore, the mechanism of the future power distribution grid with large amount of PHEVs charging load, can be looked as interactions between three nets: the transportation net, power grid and the communication net. This can be illustrated in Fig. 1.

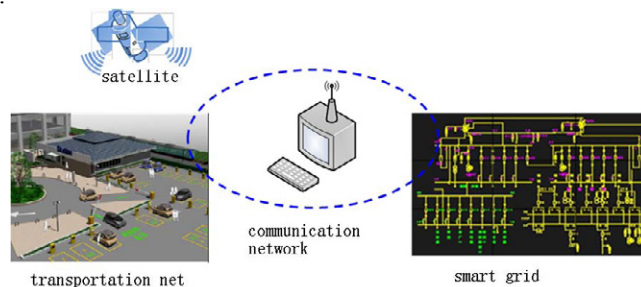


Fig. 1. The interactions between these three nets.

These three nets have different mathematical models with the different emphasis. The power grid put more emphasis on its operation security and economy. The transportation net cares the vehicles flux moving more fluently. And the communication net puts its concern on the communication system robust operation with low cost. Therefore, it's a very complex problem of the PHEVs charging management.

3. Influence of Charging Loads on the Grid

From the above discussion, it is clearly that the PHEVs charging load has the huge influence to the operation of the power grid. Based on the power energy flowing direction, we can distinguish the PHEVs operation models into charging model and generation model. The first one is that the power energy flows from the power grid to the batteries of the PHEVs. The second model means that the power flows in a converse direction and the energy stored in the batteries is injected into the power grid. Therefore, the different PHEVs operation model has the different impact on the power grid.

In charging model, the batteries of PHEVs can be looked as a load in the power grid. But different from the other common loads, PHEVs charging load has its character, such as the great power demand and the charging process controllable. It's well known that the maximum storage capacity of the PHEV battery is around 11kWh and in general the home charger has a maximum output power of 4kW [4]. With the PHEVs technology become mature, the amount of the PHEVs will follow the exponential curves in the next few years. Some research point out that in 2030, the maximum penetration degree of PHEVs will be about 30% in most cities around the world. This means that 30% of total population of vehicles will be PHEVs in 2030. Here, we can illustrate this scenario with the forecasting data of the Beijing city. According to the estimation of Beijing government, the number of vehicles in Beijing will achieve 10,000,000 in 2030. This means that about 3 million vehicles are PHEVs and they need to be charged every day. If we suppose that the charging load is about 8kWh for each PHEV, therefore the total energy consuming for all these PHEV will be as high as to 24 million kWh per day. This can lead to extra large and undesirable peaks in the electrical power consumption. Of course, the variety of PHEVs charging loads at different location also influences the system losses and voltage deviation. So, PHEVs charging load has great impact on the power system.

The other character for charging model is the controllable of the charging process. This means that the charger can decrease the battery charging current or even temporarily stop the charging for the power grid security. This will less damage the life of the battery. It's the charging process controllability that provides the convenience to realize the optimization charging schedule.

PHEVs can operate in generation model. This means the electric power stored in the batteries of the PHEVs can be injected into the power grid. Therefore, PHEVs can be looked as the distribution generation plants or the energy-stored devices. Specially, we can suppose this scenario that the PHEVs operate in charging model and store the electric energy when the power grid operate in valley point, and when the power grid operate in peak point, the PHEVs release out its power. If there are hundreds of thousand PHEVs inject their power into the grid, the total power will possibly exceed a moderate-scale generator's generation. Depend on the PHEVs stored energy and released energy, the power grid can operate in peak shaving and valley filling ways. This will increase the security and economics of the power system. Of course, this obviously increases the complexity of power systems operation.

4. Optimizing Charging Schedule of PHEVs

Optimizing charging schedule or the coordinated charging management is one of the focuses in this field. In general, the uncoordinated charging method where the vehicles are charged immediately when they are plugged in or after a fixed start delay, will lead to serious grid accidents, such as the overload of the transmission lines or the serious voltage drop at some buses. It's necessary to research coordinated charging schedule.

The familiar mathematical model is built based on optimizing technology [3]. Usually, the object is minimizing the system power losses and can be described as:

$$\min \sum_{l=1}^{t_{\max}} \sum_{l=1}^{\text{lines}} R_l \cdot I_{l,t}^2 \quad (1)$$

The constraint conditions of the model can be divided into two kinds: the power system security constraint the battery charging requirement. The first constraints can be written as following:

$$\text{s.t.1} \left\{ \begin{array}{l} \forall t, P_{i,t} - V_{i,t} \sum_{j=1}^N V_{j,t} (G_{ij} \cos \theta_{ij,t} + B_{ij} \sin \theta_{ij,t}) = 0 \\ \forall t, Q_{i,t} - V_{i,t} \sum_{j=1}^N V_{j,t} (G_{ij} \sin \theta_{ij,t} - B_{ij} \cos \theta_{ij,t}) = 0 \\ V_{j,\min} \leq V_{j,t} \leq V_{j,\max} \quad j = 1, 2, \dots, N \\ 0 \leq |I_{l,t}| \leq I_{l,\max} \quad l = 1, 2, \dots, \text{lines} \\ P_{Gi,\min} \leq P_{Gi,t} \leq P_{Gi,\max} \quad i = 1, 2, \dots, N_g \\ Q_{Gi,\min} \leq Q_{Gi,t} \leq Q_{Gi,\max} \quad i = 1, 2, \dots, N_g \end{array} \right. \quad (2)$$

where N is the total number of buses; P_i and Q_i are the net active power and reactive power injected into bus i ; $V_i \angle \theta_i$ is the voltage on bus i ; $\theta_{ij} = \theta_i - \theta_j$ is the phase difference between the voltages of bus i, j ; $G_{ij} + jB_{ij}$ is the corresponding element in system admittance matrix; N_g is the total number of generators; $V_{j,\min}, V_{j,\max}$ are the bus j voltage magnitude lower limit and upper limit; $P_{Gi,\min}, P_{Gi,\max}$ are active power lower limit and upper limit of generator i ; $Q_{Gi,\min}, Q_{Gi,\max}$ are reactive power lower limit and upper limit of generator i .

And the battery charging requirement constraint is:

$$\text{s.t.2} \left\{ \begin{array}{l} \forall t, \forall n \quad 0 \leq P_{n,t} \leq P_{\max} \\ \forall n \quad \sum_{t=1}^{t_{\max}} P_{n,t} \cdot \Delta t = C_{n,\max} \end{array} \right. \quad (3)$$

where n is the PHEVs charger number, and the $P_{n,t}$ is charging power at the time t ; P_{\max} is maximum output power of the charger; $C_{n,\max}$ is battery maximum capacity attached with the charger n . The last constraint means that at the end of cycle, the battery must be fully charged, so the power energy which flows to the battery must equal the battery capacity.

As regard this nonlinear optimization model, sequential quadratic optimization, dynamic programming, or some evolution algorithms can be used to tackle it out. But the difficulty lies that the in the application of the charging control process, the power loads on some buses, come from the forecast data. And the real data, no whether the common power loads or the vehicle's charging loads, are varied with the time t . Therefore, the above mathematical model will update dynamically.

5. Key Technology of the Communication Net

The foregoing part brings out a new problem that how to obtain the system parameters, such as the status of the generator, the load consuming amount on some buses, or the charging vehicles number in some parks, etc., must be obtained in time. This means that we should build a communication net to monitor the whole power systems and exchange the data between the power system and the charging vehicles.

In generally, this communication network can be classified into two parts. As regard to power system,

the function of the communication net can be realized by the so-called the advanced metering infrastructure (AMI), which can provide the power system operation information in detail. But the counterpart of the transportation net, such as the vehicles GPS location devices, or the transportation flux monitoring devices on the crossroad, is insufficient to provide the enough data to analyze the charging loads demand and control the vehicles charging process. Therefore, it's necessary to reinforce the vehicles communication network to exchange the data with the AMI systems.

Compared with the fiber Ethernet technology, wireless sensor network (WSN) has the great potential to be the core parts of this communication net because of its cheaper, smaller, and intelligent. ZigBee technology, Bluetooth, Wi-fi (802.11), and power line communication are the possible options to construct the WSN. But evaluate these technologies from the respect of cost and low power consumption, ZigBee fits the requirements very well as the ideal communication platform with the data rates of up to 250Kbps over a range of over 10 to 100 meters [9]. We can set these kind ZigBee devices at the charging stations, PHEVs, etc. And they can automatically construct a network for communicating related information like the state of charge of the battery, the available space for vehicles charging in the charging stations, and so on. We can also set a root node which acts as the network management and behaves as a bridge to internet. All the data can be routed through root node to the power energy management system (EMS). And under this circumstance, the PHEVs charging loads can be looked as an controllable load in the power system.

Of course, other rising technologies, such as the radio frequency identification (RFID) or the cloudy computation, also have the potential to be key technology to manage the PHEVs charging.

6. Conclusion

The smart grid faces the new challenge from the large amount of PHEVs charging loads. With the different operation model, the PHEVs have different impact to the security and economics of the power systems. Coordinate charging schedule under the smart grid environment is the fatal to solve this problem. And the AMI infrastructure of the smart grid and WSN technology are the necessary to make the whole system operation normally. Because of the complexity of the PHEVs charging management, the future works mainly focus on the coordinated schedule models, the battery technology and the PHEVs charging loads forecasting and management.

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